Turbulence Modeling in Global Ocean-Climate Simulations

Ocean-climate models are typically run at relatively low resolution (1° or $\sim$ 100km grid cells) in climate simulations due to the computational requirements of the coupled components and duration of the simulations, which might last for hundreds or thousands of model years. This resolution is well above the Rossby radius of deformation over most of the ocean domain, the typical horizontal size of eddies in the ocean. As a result, ocean-climate simulations only include the mean, large-scale flow, and not the eddies one might observe in satellite images. These eddies affect the mean circulation by transporting buoyancy and kinetic energy. Recent ocean-only simulations at resolutions of 1/10° and finer confirm that when eddy-scale dynamics are resolved, some of the more prominent biases in the mean circulation, such as the well known biases in Gulf Stream path and structure, are greatly reduced.

The goal of turbulence modeling is to capture the effects of small scale structures on the large-scale flow. In the case of ocean-climate models, this need is particularly pressing because the Rossby radius, the length scale where available potential energy is converted into kinetic energy, is not resolved except in the equatorial region. This leaves not just *part* of the mesoscale eddy spectrum unresolved, but *all* of that spectrum unresolved (Fig. 1) except perhaps in the region in which the equatorial jets occur. Thus, parameterization of those effects becomes a necessity.

The Lagrangian-Averaged Navier-Stokes alpha (LANS-α) model is a turbulence parameterization that has been shown to capture some of the most important features turbulence at lower resolution than non-LANS-α simulations. The LANS-α model improves turbulence statistics with an additional nonlinear term and a smoothed advecting velocity. It had previously been implemented in turbulent pipe flow, large eddy simulations, shallow water models, and quasigeostrophic models, all with promising results.

As part of his post-doctoral research appointment at the Center for Nonlinear Studies at LANL, Mark Petersen implemented the LANS-α model in the Parallel Ocean Program (POP). POP, developed at LANL, is the ocean component of NCAR's Community Climate System Model, and is used for twenty-first century climate simulations by the Intergovernmental Panel on Climate Change (IPCC). POP uses finite differences to discretize conservation of momentum, mass, energy, and tracers.

POP's splitting of the barotropic (depth integrated) and baroclinic (individual z-level) velocities presented particularly difficult challenges in the implementation of LANS-α. The full algorithm, as derived from the original LANS-α equations, requires
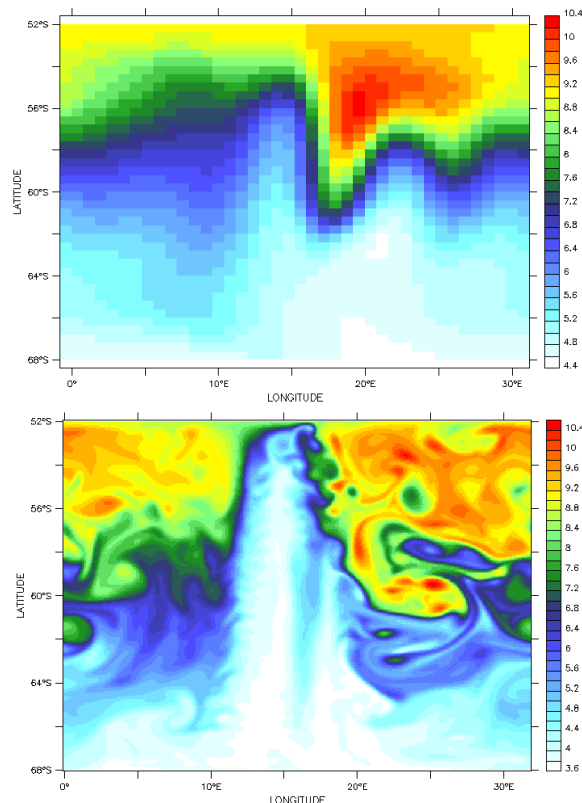

Figure 1: Surface temperature (in ^{o}C) of an ocean simulation using a horizontal grid resolution used in climate modeling ($0.8^o \times 0.8^o$, top) and a high resolution ocean simulation ($0.1^o \times 0.1^o$, bottom). Climate model simulations do not resolve the Rossby Radius, and so do not include eddies and their associated turbulent fluxes.

a nested iteration, which makes it too inefficient to be feasible as a turbulence model. Because of this, a reduced algorithm was developed that is two to three times faster than the full algorithm, but produces equivalent results [1].

A linear stability analysis shows that both the full and reduced POP-α algorithms benefit from the way the LANS-α equations take into account the effects of the small scales on the large. Both algorithms are stable, have an effective Rossby deformation radius that is larger than the deformation radius of the unmodeled equations, and reduce the propagation speeds of the modeled Rossby and gravity waves relative to the unmodeled waves at high wave numbers [1].

A second issue was the choice of smoothing operator used to obtain the smooth advecting velocity. The LANS-α equations use a Helmholtz inversion for this operator. Simple smoothing filters that average nearest neighbors can produce similar results at a much cheaper cost. However, the filter weights must be
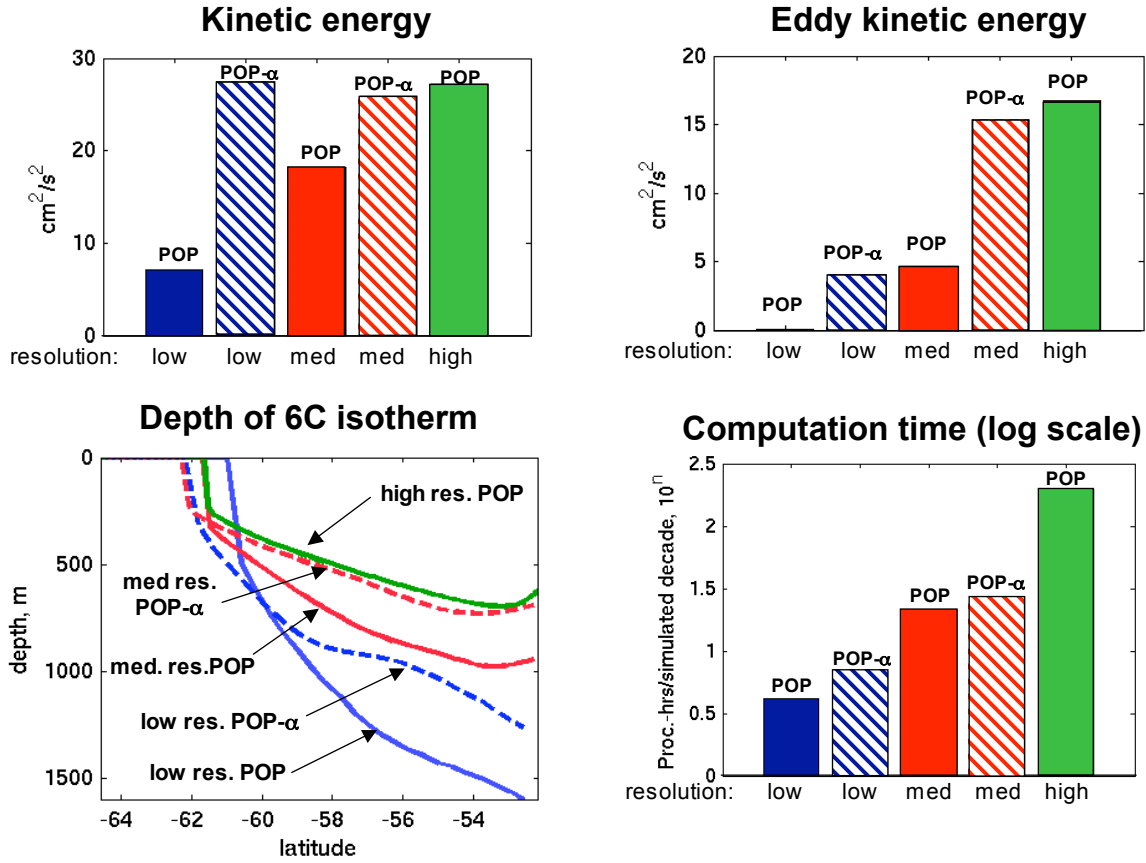
Figure 2: Comparison of POP alone and POP with LANS-α (POP-α) in a periodic channel domain, where low resolution is 0.8^o, med is 0.4^o, and high is 0.2^o. POP-α is able to obtain turbulence statistics like a doubling of resolution using standard POP, with only a small increase in computational time.

chosen carefully to prevent pressure-velocity instabilities. Certain ranges of filter weights are unstable—this has been shown analytically and confirmed with numerical experiments [2].

Simulations using LANS-α in the POP primitive-equation ocean model resemble doubled-resolution simulations of standard POP in statistics like kinetic energy, eddy kinetic energy, and potential temperature fields (Fig. 2). The computational cost of adding LANS-α is only 27% for our most efficient implementation, as compared to a factor of 8—10 for a doubling of resolution.

We expect the LANS-α turbulence parameterization to be particularly effective at an ocean model grid resolution that has been coarsened by approximately a factor of two to four, relative to the resolution required to bring out a vigorous mesoscale eddy field. So-called eddy-resolving ocean modeling, capturing such a vigorous eddy field, is known to require a grid resolution on the order of $0.1°$. Future work will address the question of the interaction of LANS-α with other turbulence models, including constant coefficient hyperviscosity, Gent-McWilliams isopycnal tracer mixing, and the Leray model. These results, to be published in the near future, will consider the merits of LANS-α relative to competing models in the context of primitive-equation ocean models.

References

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[2] Mark R. Petersen. Efficient form of the LANS-alpha turbulence model in a primitive-equation ocean model. *submitted to JCP*, 2007.

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